

The Temperature and Opacity of Atomic Hydrogen in Spiral Galaxies

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ABSTRACT

We analyze the resolved neutral hydrogen emission properties of a sample of eleven of the nearest spiral galaxies. Between 60 and 90% of the total H I line flux within the optical disk is due to a high brightness network (HBN) of emission features which are marginally resolved in their narrow dimension at about 150 pc and have a face-on covering factor of about 15%. Averaged line profiles of this component are systematically non-Gaussian with a narrow core (less than about 6 km s^{-1} FWHM) superposed on broad Lorentzian wings (30 km s^{-1} FWHM). An upper limit to the gas temperature of 300 K follows directly from the narrow line profiles, while simple modeling suggests kinetic temperatures equal to the peak emission brightness temperature (80–200 K) in all cases but the outer disks of low mass galaxies, where the HBN becomes optically thin to the $\lambda 21 \text{ cm}$ line. Positive radial gradients in the derived kinetic temperature are found in all spiral galaxies. The distributions of brightness temperature with radius in our sample form a nested system with galaxies of earlier morphological type systematically displaced to lower temperature at all radii. The fractional line flux due to the HBN plummets abruptly near the edge of the optical disk where a diffuse outer gas disk takes over. We identify the HBN with the Cool Neutral Medium.

Subject headings: galaxies: ISM — galaxies: kinematics and dynamics — galaxies: spiral — radio lines: galaxies

1. Introduction

The last three decades have seen substantial progress in our understanding of the neutral interstellar medium of galaxies, as summarized for example in the review by Kulkarni & Heiles (1988). Even so, there are important elements of the global theory which are still rather poorly defined. One of the most basic of these is the intrinsic topology of the neutral gas. Historically, it was convenient to characterize the neutral ISM in the solar neighborhood as a distribution of “standard” diffuse spherical clouds of atomic hydrogen with typical radii of perhaps 5 pc (Spitzer 1978). This was done even though earlier observational studies (Heiles 1967, Verschuur 1974) had demonstrated that the majority of atomic structures were organized into large sheets or filaments

with dimensions of at least tens of pc. The basic question has remained, however, of whether the atomic gas topology more closely resembles isolated concentrations in a lower density substrate (the “raisin pudding” model), a moderate density matrix with low density cavities (the “Swiss cheese” model) or perhaps a self-similar distribution of structures over some range of spatial scales. There is also the question of whether this topology might depend on location within the galactic disk.

By turning to nearby external galaxies it becomes much easier to achieve a global inventory of the neutral gas topology. An entire galactic disk, at a common distance and more favorable orientation, can then be studied simultaneously. The only drawback to this approach is the difficulty of obtaining sufficient physical resolution and sensitivity. This drawback has been serious enough that it has precluded serious study of the neutral atomic ISM of external galaxies until rather recently. The many published studies of H I emission in external galaxies have instead concentrated primarily on the global gas dynamics and kinematics. And even though 100 pc by 8 km s^{−1} resolution was available about ten years ago in H I studies of the Local Group galaxies M31 and M33 (Brinks & Shane 1984, Deul & van der Hulst 1987) the question of global topology of the neutral ISM in these systems has not yet been addressed. What has emerged, from these and more recent studies, is the recognition that bubble and filamentary emission structures are indeed the norm rather than the exception.

A related fundamental concern is the physical state of the gas itself. What are the typical densities and temperatures involved and do these properties depend in any systematic way on position in a galaxy. Theoretical treatments of H I thermodynamics (Field 1965, Draine 1978, Shull & Woods 1985, Wolfire et al. 1995) lead to the clear prediction that two distinct phases of neutral atomic hydrogen are to be expected. A warm phase, the Warm Neutral Medium (WNM), with density of order 0.1 cm^{−3} and temperature of about 8000 K should predominate at low interstellar pressures, while a cool phase, the Cool Neutral Medium (CNM) with density > 1 cm^{−3} and temperature between about 50 and 250 K should become dominant at high interstellar pressures. Strong observational evidence for these two distinct components dates back to some of the earliest comparisons of H I emission and absorption along Galactic lines-of-sight (Clark 1965, Radhakrishnan et al. 1972). However, given the paucity of background sources with which to map out the distribution of absorption, it has remained difficult to associate specific spatial morphologies to the two atomic phases, or to track any possible variation in their physical parameters with location in the Galaxy.

This problem can also be usefully addressed by turning to nearby external systems, where a more favorable orientation can facilitate unambiguous identification of particular components and allow determination of their location within a galaxy. The scarcity of suitable background sources for the measurement of H I absorption in the direction of nearby galaxy disks makes this a difficult undertaking. Even so, a comparison of H I emission and absorption spectra through the disk of M31 with 35 pc by 5 km s^{−1} resolution (Braun & Walterbos 1992) reveals that significant absorption opacities have a one-to-one correspondence with regions of high

emission brightness. Although this may sound like a trivial statement, the implications are quite profound. *H I emission structures with a high brightness temperature are relatively opaque, so that the emission brightness approaches the gas kinetic temperature when the structure has been spatially and kinematically resolved.* Furthermore, the cool phase kinetic temperature in M31 is observed to increase systematically from about 70 K at radii of 5–10 kpc to about 175 K at radii of 10–20 kpc. The identical positive radial gradient is observed directly in the peak emission brightness temperature! This close correspondence of emission brightness and kinetic temperature implies that the high brightness emission features: (1) have been resolved (at about 100 pc by 5 km s^{-1}) and (2) have H I opacities greater than about unity over the range in radius where the temperatures agree.

In this paper we will analyze the H I emission properties, observed with a resolution of about 100 pc by 6 km s^{-1} , of a sample of eleven of the nearest spiral galaxies beyond the Local Group. The basic data have been presented in Braun (1995, hereafter referred to as B95) so only the most relevant points concerning the observations and data reduction are summarized below in § 2. An important point to stress at the outset is that although this database has high spatial resolution it also has full sensitivity to the largest structures and accurately recovers the total integrated emission of each galaxy. High resolution images of both the peak and the integrated brightness of all the sample galaxies are presented in B95. Images of the peak brightness of H I emission at this physical resolution are particularly illuminating, in that they reveal the existence of a filamentary network of high brightness temperature ($> 50 \text{ K}$) emission features within the star-forming disk of each galaxy. These features include, but are not restricted to, the spiral arms seen in optical, molecular and dust tracers.

In the few cases where the presence of an appropriate background source has allowed a search for H I absorption, gas kinetic temperatures are implied which are consistent with the observed brightness temperature, just as was seen previously in the case of M31. This high brightness network (or HBN) gives every indication of representing a phase of the atomic gas which has substantial H I opacity. An interesting pattern was noted in B95 for the peak brightness temperature of these features to increase systematically with radius. It seems that there may be a systematic variation with radius of either or both of (1) the gas kinetic temperature and (2) the typical H I opacity of the high brightness H I in normal spiral galaxy disks.

In § 3 we will derive the properties of the high brightness H I network as a function of radius in our sample galaxies. Critical topological and physical properties such as the spatial scale-size, velocity width, fractional H I line flux, surface covering factor and peak brightness temperature will be determined together with their radial dependencies. In addition, median co-aligned emission spectra will be generated and analyzed within annular zones. The extremely narrow line-width of the high brightness emission core allows an upper limit of about 300 K to be placed on the gas kinetic temperature. There can be no doubt that the high brightness network represents high opacity concentrations of the cool atomic phase of neutral hydrogen.

2. Observations and Data Reduction

Neutral hydrogen observations of the eleven program galaxies were obtained with the VLA between March 1989 and November 1990. The B, C and D configurations (with effective integration times of about 7, 0.5 and 0.4 hours) were utilized to image a region 0.5 degree in diameter at 6 arcsec resolution for each of the eight Northern galaxies. In addition, a small hexagonal mosaic in the D configuration (with 0.4 hours effective integration on each of 7 positions) was used to image a 1 degree diameter field at 65 arcsec resolution. Similar resolution and sampling was obtained for the three southerly galaxies by observing in the BnA, CnB and DnC configurations. Observing dates, field centers and other particulars are summarized in Table 1. Namely, the galaxy name in column (1), the B1950 pointing center in (2), the observation dates for the three observed configurations in (3), the central velocity and number of frequency channels in (6) and (7). The assumed inclination, position angle of receding line-of-nodes and major axis radius at which the blue optical surface brightness is 25 mag arcsec² (from de Vaucouleurs et al., 1991, hereafter the RC3) is given in columns (8), (9) and (10). The galaxy type, approximate distance, total blue magnitude and luminosity are given in columns (11) to (14). Standard calibration and imaging techniques were used to produce a series of narrow-band images separated by 5.16 km s⁻¹ over a velocity range of 330 km s⁻¹ (or 660 km s⁻¹ when necessary) centered on the nominal heliocentric systemic velocity of each galaxy. Since a uniform frequency taper was applied in the correlator, the effective velocity resolution was 6.2 km s⁻¹.

Data attributes are summarized in Table 2, both at the full resolution as well as after smoothing to spatial resolutions of 9, 15, 25 and 65 arcsec. The best fitting elliptical Gaussian beam parameters and the beam integral at full spatial resolution are listed in columns (2) and (3). The rms sensitivity in a single frequency channel is given in terms of flux density and surface brightness in columns (4) and (5). The surface brightness sensitivity after convolution to lower spatial resolutions is given in columns (6) through (9) of the table. Total detected line fluxes within the contiguous region bounded by a peak brightness of 4 and 0 Kelvin (as seen at 65 arcsec resolution) are listed in columns (10) and (11). Recent single dish measurements in the literature (as tabulated in Huchtmeier and Richter, 1989) generally lie between these two values.

The line-of-sight emission and absorption properties toward the 54 brightest continuum sources in the 11 observed fields were derived and are presented in Table 3 of B95.

3. Results

Examination of the peak H I brightness images in Figs. 1–10 of B95 reveals how the distribution of atomic gas in our sample galaxies becomes decomposed at 100 pc linear resolution into a high brightness filamentary network (or HBN) of H I features. The continuity is best seen at low to moderate inclinations, while edge-on systems like NGC 55 and 4244 appear entirely filled as seen in projection. This network corresponds globally to both the grand-design, as well as the

flocculent, spiral arms traced by massive star formation and by dust lanes in the various galaxies.

3.1. Assessing Data Purity

Before undertaking an analysis of the HBN, we will demonstrate that we are dealing with a real population of features rather than some set of random noise peaks. To begin with, let us consider the noise properties of the data-cubes. In Fig. 1a we present a histogram of the pixel brightnesses seen in several velocity channels near the edge of the observed band toward NGC 5457, where no line emission was apparent. The noise distribution is quite accurately Gaussian down to at least plus and minus 4σ and is fit by an rms fluctuation level of 1.05 mJy per beam area. A Gaussian function with this dispersion is overlaid on the histogram as the solid line. Careful inspection does reveal a small symmetric excess of pixels between about 3 and 4σ with respect to the $\sigma = 1.05$ Gaussian distribution. This portion of the distribution is fit best by the $\sigma = 1.07$ Gaussian indicated by the dashed line in the figure. This difference of 2% in the rms fluctuation level is indicative of the accuracy to which the rms can be determined and the degree to which the data conform to Gaussian statistics.

We will now consider the criteria which permit optimum detection of emission features. The primary beam corrected image of the peak observed brightness temperature in NGC 5457 is shown in Fig. 2a. It is clear that the signal-to-noise ratio in our full resolution data is not overwhelming. The typical brightness sensitivity is 15–20 K at the field center, while peak brightnesses on the filamentary ridgelines vary between about 50 and 200 K. We have isolated the high brightness network from the general field by applying a spatial mask to the full resolution images of peak brightness. This mask was defined by the regions within the 5σ contour in the 15 arcsec resolution images of peak brightness. This cut-off level corresponds to about 25 K at 15 arcsec resolution at the field center and climbs to 50 K at a radius of about 1800 arcsec (due to the primary beam correction). The masked version of the NGC 5457 image is shown in Fig. 2b to illustrate the effect of applying this mask.

The degree of data purity within the masked database is illustrated in Fig. 2c, where we plot the line-of-sight velocity which corresponds to each pixel shown in Fig. 2b. It is important to stress that we are not simply displaying a velocity field which has been generated by calculating a weighted mean along each spectrum of the data-cube, but rather the actual velocity which corresponds to the single pixel with highest brightness at each position. Random noise peaks will have a random velocity associated with them drawn from the entire range of observed velocities. The distribution of velocities in Fig. 2c is not random, but varies systematically in accordance with the actual kinematics of the galaxy. A small, but visible contribution of random velocities is indeed visible, particularly near the edges of the masked distribution.

We can obtain a quantitative estimate of the degree of noise contamination by producing a histogram of the velocities near either end of the major axis of the galaxy where the galactic

kinematics dictate an approximately constant line-of-sight velocity for real emission features. In Fig. 1b we present the histogram of observed velocities (shown in Fig. 2c) for a sub-field centered on the South-West major axis of NGC 5457. The number density of pixels having an aberrant velocity (about 100 per velocity channel) implies that as many as 23% of the (21,000) pixels isolated by the spatial mask in this sub-field are likely to be noise interlopers. If we apply the additional constraint that the peak brightness associated with each velocity must exceed 3σ we get the image shown in Fig. 2d. Inspection shows that this velocity field is substantially cleaner and examination of the corresponding histogram of the same major axis sub-field in Fig. 1c reveals that 5.2% of the pixels (relative to the area isolated by the spatial mask) are likely to be noise peaks given the number density of aberrant velocities (about 20 per velocity channel).

This can be compared with the expectation based on perfectly Gaussian noise. In that case we would expect to have 0.13% of the values in a single image exceed 3σ . Since the peak brightness image has been derived from a cube containing about 40 *independent* velocity channels, we would expect it to suffer from a 5.4% contamination by random noise peaks exceeding the 3σ level. This is in excellent agreement with the estimate derived above. Constraining the selection of pixels to only those for which the peak brightness exceeds the 4σ level leaves less than 0.27% contamination of the mask area by random noise peaks as illustrated in Fig. 1d. The expectation based on purely Gaussian noise is that only 0.13% of the random noise peaks should exceed this level in an image of peak brightness based on 40 independent velocity channels. This discrepancy with respect to the Gaussian value would arise if we had underestimated the true rms fluctuation level by only 3%. Both the magnitude and sense of this discrepancy are in agreement with the actual noise histogram shown in Fig. 1a.

In practical terms then, of the 85,000 pixels isolated by the spatial mask in NGC 5457, 8895 are found to have peak brightnesses exceeding 4σ , but 230 of these are likely to be noise peaks. This practical example illustrates the utility of applying the spatial mask to the data as a first step in isolating real emission features. If the entire image of 10^6 pixels were being employed, the 8665 real emission peaks would be contaminated by an additional 2830 noise peaks exceeding 4σ . This expectation is confirmed to better than 1% accuracy by a direct measurement of the number of peaks exceeding 4σ in the entire image.

For the sake of completeness, we should also point out the potential pitfalls of employing such a spatial mask based on a high significance level in a lower resolution image. The lower resolution mask will encompass the brightest, compact emission features only if they are spatially associated with more extended regions of emission. Any truly isolated compact peaks which have only marginal significance will be lost by this method, since the signal in the smoothed image will decline more rapidly than the noise level. For our purposes, this is a risk worth taking since the factor of ten improvement in data purity is essential, even at the expense of losing some real emission features.

We are now in a position to calculate the actual degree of noise contamination which effects

data satisfying our selection criteria of (1) lying within the spatial mask defined above, and (2) having a peak brightness in the spectrum exceeding 4σ . The contamination level can be quite simply described by the ratio of the expected number of noise peaks exceeding 4σ within the spatial mask (using the measured contamination rate of 0.27% over 40 independent channels) to the number of such features which are actually observed. In the case of NGC 5457 we derive a contamination level of 2.6%. Contamination levels were calculated for all of the analyzed galaxies and are listed in column (14) of Table 2. These vary from 1% in the case of NGC 4236 to about 8% in the case of NGC 7793, but are typically about 2.5%.

There can be no doubt that we are dealing with a real population of features, even though each individual detection has only a modest signal-to-noise ratio. The properties of the population itself can be determined with high precision by averaging within sub-samples. Measurement noise can be expected to decrease as the square root of the number of independent samples being combined. With our knowledge of the noise contamination levels we can also make accurate predictions of possible systematic effects which these might give rise to.

3.2. The Radial Distribution of Peak Brightness

The mask shown in Fig. 2b is wide enough to include the wings of the instrumental response and therefore allows measurement of integrated fluxes from this component. On the other hand, the peak brightness of filamentary ridge-lines is substantially diluted by a simple average over the mask. An estimate of the true peak brightness at each radius was made by forming a histogram of the brightnesses exceeding 4σ observed within the masked elliptical annuli and identifying the brightness at which 80% of the pixels are included in the histogram. Changing the histogram cut-off level to 70% or even 50% of the included pixels only resulted in a modest overall decrease in peak brightness without further influencing the observed radial trends. Error bars were calculated from the primary beam corrected rms level appropriate for each annular zone and the (square root of the) number of contributing image points.

The radial distribution of peak brightness was determined in this way for each of the low and moderate inclination program galaxies. (No model-independent radii could be associated with the emission regions in the highly inclined galaxies NGC 55 and 4244.) These distributions are shown in panel (a) of Figs. 3–9 together with the average surface density of integrated HI. Positive radial gradients of the peak brightness temperature are detected in all galaxies except NGC 2366. Values vary from typically 80 K at small radii for most galaxies to more than 200 K at large radii in the case of NGC 5457.

3.3. Spatial and Velocity Coherence

Two physically important properties of the HBN are the spatial scale-size and the velocity dispersion. Visual inspection of Figs. 1–10 of B95 already suggests that when the network is seen relatively face-on it has a thread-like character which appears to be only marginally resolved in one dimension with our maximum angular resolution of about 6 arcsec which corresponds to 100 pc at the average galaxy distance of 3.5 Mpc. In order to obtain a global measure of the spatial coherence we have generated images of the ratio of peak observed brightness after smoothing the data-cubes to 9 arcsec and 15 arcsec with respect to the peak brightness observed at full spatial resolution. If our initial datacube is written as $I(x,y,v)$, and $P(x,y)$ is the image of maximum brightness over all “v” at each spatial pixel, then we are first producing datacubes smoothed to 9 and 15 arcsec, $I_{9''}(x,y,v)$ and $I_{15''}(x,y,v)$, their corresponding images of peak brightness, $P_{9''}(x,y)$ and $P_{15''}(x,y)$, and finally the ratio images, $SC_{9''}(x,y) = P_{9''}(x,y)/P(x,y)$ and $SC_{15''}(x,y) = P_{15''}(x,y)/P(x,y)$.

Only those pixels which were contained in the spatial mask *and* had signal to noise greater than 4 (taking account of the primary beam correction) in the full resolution cube were used in this comparison. An unresolved linear source would experience a diminished peak brightness by a factor of about $6.5/9 = 0.72$ and $6.5/15 = 0.43$ in these two cases. Values of about 0.77 are typically seen at 9 arcsec resolution and 0.59 at 15 arcsec. The actual spatial structure is of course more complex than a simple line. This will tend to keep the brightness ratio from falling as quickly with spatial smoothing as it might otherwise. Another consideration is that a faint diffuse background is present on large angular scales which also contributes to a systematically higher brightness ratio after smoothing. In view of these considerations the observed degree of peak dilution is consistent with the HBN being only marginally resolved in its narrow dimension with 100 pc spatial resolution.

The radial dependence of diminished peak brightness was determined by taking the median in elliptical annuli and is illustrated in panel (b) of Figs. 3–9. It is striking that inside of about R_{25} (the radius at which the B band surface brightness has declined to 25 mag arcsec⁻²) the distributions are relatively flat, while at about this radius a marked systematic decline in the spatial coherence becomes apparent. Coherence values seen at large radii are consistent with linear structures which are *unresolved* even at the full 100 pc linear resolution.

A similar procedure was employed to obtain a global measure of the velocity width of the HBN. The full resolution data-cubes were smoothed in velocity to a resolution of 10.3 and 20.5 km s⁻¹ to create $I_{10km}(x,y,v)$ and $I_{20km}(x,y,v)$ and the ratio was generated of the resulting peak brightnesses to those observed originally, $VC_{10km}(x,y) = P_{10km}(x,y)/P(x,y)$ and $VC_{20km}(x,y) = P_{20km}(x,y)/P(x,y)$.

As before, only those pixels within the spatial mask and with signal to noise greater than 4 in the full resolution database were used. Isolated, unresolved features in velocity should be diminished in brightness by a factor of $6.2/10.3 = 0.60$ and $6.2/20.5 = 0.30$ for these two cases. In fact, median values of 0.75 were found at 10 km s⁻¹ and 0.54 at 20 km s⁻¹. The radial dependence

of velocity coherence was found to accurately track the spatial coherence as shown in panel (b) of Figs. 3–9. The same trend noted previously is also seen in the velocity coherence, namely that near R_{25} a rapid decline of the coherence with radius is observed. Velocity coherence values at the largest radii are consistent with isolated spectral features which are unresolved at the full 6.2 km s^{-1} velocity resolution.

3.4. Integrated Line Flux and Surface Covering Factor

The integrated line flux was determined for the HBN in each galaxy using the spatial mask described and illustrated above (the 5σ contour in the 15 arcsec resolution images). The ratio of line flux in the network to the total line flux (using the 4 K criterion in the 65 arcsec resolution images) is given in column (12) of Table 2. Between 20 and 85% of the total line flux is detected within the high brightness filaments. The ratio of surface area occupied by these features versus the total surface area of the disk (using the same masks as for the flux determination above) is given in column (13) of Table 2. Between about 6 and 50% of the total disk area is occupied by the high brightness network. These values represent an upper limit to the global surface covering factor of the high brightness network since the spatial isolating mask is wider than the actual ridge-line.

It is instructive to consider the radial distribution of fractional flux and surface covering factor of these features, rather than just considering the global ratios noted above. The fractional line flux of the HBN relative to the total line flux is plotted as a function of radius for the program galaxies in panel (c) of Figs. 3–9. It is striking that within the actively star-forming portion of each galaxy disk (indicated crudely by R_{25} in each panel) the fractional line flux in HBN is between about 60 and 90%. Coinciding closely with the edge of the star-forming disk is a precipitous decline in the fractional line flux. This is in contrast to the total line flux. The accumulated H I line flux as a function of radius is also shown in the figure for both the total and HBN components. While the accumulated HBN flux saturates at R_{25} , the accumulated total flux is still rising almost linearly through about 1.5–2.0 times R_{25} .

The face-on surface covering factor is also plotted as a function of radius in the figures. The fractional surface area of the HBN was scaled down by the ratio of the average T_B to the peak T_B (as defined above) in each elliptical annulus to account for the fact that the mask used to isolate the HBN is wider than the actual distribution and therefore gives rise to a peak dilution. Face-on, dilution corrected surface covering factors of the HBN are typically about 15% within R_{25} .

3.5. Median Emission Spectra of the HBN

Although each spectrum along an individual spatial pixel of our data-cubes has only a modest signal-to-noise ratio, a glance at Fig. 2 illustrates that there are many independent spectra

available for combined study. We have generated high signal-to-noise spectra for further analysis by considering annular ellipses in the galaxies (corresponding to an interval in radius) and forming the median spectrum of all those pixels satisfying our selection criteria after aligning them to the velocity of the peak observed brightness. These spectra are displayed in panel (d) of Figs. 3–9. The error bars are calculated from the actual rms fluctuation level at the relevant radius and the (square root of the) number of contributing points. In general, the spectra are characterized by an extremely narrow core component superposed on broad line wings which often extend over a velocity interval of 100 km s^{-1} at significant intensity.

Recall that in §3.1 we have demonstrated that by applying the spatial isolating mask and accepting only those pixels with a brightness exceeding 4σ we have insured a high degree of data purity. The degree of remaining noise contamination is typically 2.5% as listed in column (14) of Table 2 for our program galaxies. With this level of noise contamination, there should be no discernible systematic effect on the combined spectra. If on the other hand, a large fraction of noise spectra were included in the combination, there would be an enhanced central pixel superposed on a background that would average to zero. The similar character of such a noise bias to that displayed by the combined spectra was an important reason for the careful examination of the noise properties of the data already described in §3.1. We are convinced that we do, in fact, understand the noise properties of the data rather well. Even so, we have attempted to test for the presence of a significant noise bias by further constraining the data acceptance criterion to the 4.5, 5 and subsequently 5.5σ level. No difference in the resulting line profiles was found, but only an increasing rms noise level in accordance with the decreasing number of pixels. It is probably worth noting that H I emission profiles such as those illustrated in panel (d) of Figs. 3–9 have never been previously obtained. Only by observing with 100 pc spatial resolution has it become possible to resolve out both the overall gradient of galactic rotation (with typical amplitude of about $10 \text{ km s}^{-1} \text{ kpc}^{-1}$) and various systematic discontinuities like those due to spiral arm shocks. The extremely narrow core of the line profile, with a dispersion of less than about 2 km s^{-1} , allows an upper limit of about 300 K to be placed on the kinetic temperature of the emitting gas. This is a strict upper limit, since some degree of turbulent broadening may also be present, and any opacity effects will further broaden the profile. It is probably most appropriate to characterize the line core as consistent with a thermal linewidth commensurate with the brightness temperature and only a very modest degree of additional broadening. The broad pedestal underlying the line core extends over almost 100 km s^{-1} and may arise within either or both of a more turbulent or much warmer component.

We have fit the HBN spectra with a simple physical model consisting of two types of gaseous components with a sandwich geometry. A central layer is assumed to have a line opacity which is Gaussian in velocity,

$$\tau_G(v) = \tau_G(0)e^{-0.5(v/\sigma_G)^2} \quad (1)$$

with a thermal velocity dispersion and central opacity given by,

$$\sigma_G = 0.0912\sqrt{T_C} \quad (2)$$

and

$$\tau_G(0) = \frac{N_{HC}}{1.83 \times 10^{18} \text{cm}^{-2} T_C \sigma_G \sqrt{2\pi}} \quad (3)$$

The outer layers are arbitrarily assumed to have a Lorentzian dependance of opacity on velocity,

$$\tau_L(v) = \frac{\tau_L(0)}{v^2 + (\Delta_L/2)^2} \quad (4)$$

in terms of the Lorentzian FWHM, Δ_L , and the central opacity given by,

$$\tau_L(0) = \frac{1}{2} \frac{N_{HL} \Delta_L}{1.83 \times 10^{18} \text{cm}^{-2} T_C 2\pi} \quad (5)$$

The observed emission brightness is then given by,

$$T_B(v) = \begin{aligned} & (T_C - T_C e^{-\tau_L}) \\ & + (T_C - T_C e^{-\tau_G}) e^{-\tau_L} \\ & + (T_C - T_C e^{-\tau_L}) e^{-\tau_G} e^{-\tau_L} \end{aligned} \quad (6)$$

in terms of the four variables, T_C , Δ_L , N_{HC} and N_{HL} . We have not indicated the explicit velocity dependence of τ_G and τ_L in the equation for T_B for the sake of compactness. Also note that the total column density of the Lorentzian component has been divided equally in two parts, one behind and one in front of the thermal component. All components are assumed to have the same kinetic temperature, T_C . The resulting model spectra of $T_B(v)$ were smoothed with a 6.2 km s^{-1} FWHM function to simulate the observational data. Least squares fits for these model parameters are listed in Table 3 for the annular zones in each galaxy. For each model parameter we also list the deviations which lead to a doubling of χ^2 when the other parameters are held fixed. The smoothed solutions are overlaid on the spectra as the solid lines in panel (d) of Figs. 3–9.

Although we have attempted to fit the data with physically plausible components, our decomposition is obviously non-unique. For comparison, we have also carried out numerous other types of decomposition; ranging from simple two component Gaussian fits to variants of the Gaussian plus Lorentzian fit in which the Gaussian dispersion was held fixed at specific values (to simulate a significant turbulent component) rather than varying in accordance with the kinetic temperature. Those solutions were discarded since besides not providing any physical insight, they were also found to have systematic residuals in the line shoulders and a higher rms deviation.

Three of our four free parameters were determined quite robustly by the least squares fitting procedure; namely the kinetic temperature, T_C , together with the Lorentzian linewidth and column density, Δ_L and N_{HL} . This is because the kinetic temperature is well-constrained by the core height and width, while the Lorentzian parameters are well-constrained by the optically thin line wings. Kinetic temperatures between about 85 and 230 K were derived with a typical error of about 10%. It is important to bear in mind that even the solutions for the lowest kinetic temperatures in Table 3 such as $T_C = 85 \text{ K}$, for which $\sigma_G = 0.92 \text{ km s}^{-1}$, are accompanied by a sufficient peak opacity that the resulting line profile has a FWHM $\sim 5 \text{ km s}^{-1}$, which is comparable

to the velocity resolution of our spectra. Lorentzian linewidths were found to vary between about 13 and 42 km s⁻¹. The associated column densities, N_{HL} , were sufficient to account for basically all of the *apparent* column density, N_{HA} , which follows from the assumption of negligible H I opacity in each spectrum. The actual column density associated with the core component, N_{HC} , was much more poorly constrained in those frequent cases when the implied peak line opacity ($\tau_{max} = \tau_G(0)$ listed in Table 3) was high. As the peak line opacity increases, its impact on the line shape becomes increasingly subtle due to the exponential dependance in eqn. 6. Central opacities in excess of about 5, should be regarded as formal fit solutions, but should not be taken literally. The quoted errors on both N_{HC} and τ_{max} reflect this uncertainty.

Cool gas in the line core sometimes accounts for only 20% of the total H I column as found in the case of NGC 2366 or as much as a factor of 10 more than in the line wings as found for NGC 5457. Although the individual values of N_{HC} are very uncertain for large τ_{max} , the general trends do seem significant. High line opacities are derived at all radii in the cases of NGC 2403, 3031 and 5457 and in the inner disks of NGC 247, 4236 and 7793. Some galaxies seem to be characterized by rather opaque filaments which can harbor a substantial quantity of “hidden” atomic gas. More accurate modeling of the intrinsic lineshape would be possible with higher sensitivity and, in particular, higher velocity resolution data.

The derived variation of T_C with radius is in good agreement with that of the peak brightness temperature data as shown in panel (a) of Figs. 3–9, whenever the line core opacity becomes substantial. Positive radial gradients of T_C are derived in all cases but that of NGC 2366. Good numerical agreement of the derived T_C with the observed peak T_B is found at all radii in the cases of NGC 2403, 3031 and 5457 and in the inner disks of NGC 247, 4236 and 7793. Systematically higher values of T_C relative to the peak T_B are derived for NGC 2366 and beyond the inner disk of NGC 247, 4236 and possibly 7793 in conjunction with a lower derived line-core opacity. The systematic nature of this departure, increasing with radius in only the lowest mass galaxies of our sample, is very suggestive of a systematic decrease in the HBN opacity with radius.

3.6. Median Emission Spectra of the Diffuse Disk

We attempted to carry out a similar procedure to produce high signal-to-noise spectra of the faint diffuse emission in inter-arm regions and beyond the star forming disk of our program galaxies. To this end, we employed the 65 arcsec resolution data-cubes to extract the median co-aligned spectra within elliptical annuli after application of our data selection criteria. In this case, a spatial mask was specified interactively by defining a contour which enclosed the contiguous region over which a smoothly varying radial velocity was observed associated with the pixel having peak brightness along each spectrum. Subsequently, only those pixels for which the peak brightness exceeded 4σ but was less than 7.5 K were included in the combination. Noise contamination rates were calculated as before and were in all cases less than 1.2%. The upper limit to the accepted brightness of 7.5 K was chosen after inspection of the peak brightness images

to eliminate as much as possible of the “bleeding” of high brightness features (at this low spatial resolution) into inter-arm and outer disk zones. Only in a few cases did it prove possible to isolate such low brightness regions in the inner disks. The best example of the resulting spectra is given in Fig. 10 for the case of NGC 5457.

A major difficulty with the interpretation of spectra obtained at this relatively low resolution (65 arcsec corresponding to about 1 kpc) is the significant contribution of galactic kinematics to the shape of the line profile. We have estimated the expected degree of line broadening within the beam by forming images of the local velocity gradient, $\nabla(x, y)$, defined by,

$$\nabla(x, y) = \left[\left(\frac{|V(x, y) - V(x + \Delta, y)| + |V(x, y) - V(x - \Delta, y)|}{2} \right)^2 + \left(\frac{|V(x, y) - V(x, y + \Delta)| + |V(x, y) - V(x, y - \Delta)|}{2} \right)^2 \right]^{1/2} \quad (7)$$

in terms of the velocity, $V(x, y)$ and a spatial offset Δ . $\nabla(x, y)$ was generated for $\Delta = 75$ arcsec and its median value was calculated for the pixels contributing to each spectrum shown in Fig. 10. This gradient, scaled to the beam FWHM by multiplication with a factor 65/75, is indicated by a horizontal error bar plotted at the half intensity level inside each spectrum. For a uniform spatial distribution of gas with a negligible intrinsic linewidth we would expect an observed FWHM comparable to that indicated by the bar. It is clear from the figure that the observed linewidth is often dominated by the effects of beam smearing. This effect is strongly inclination dependent and only in the case of NGC 5457 did it seem worthwhile to proceed with further analysis of the low resolution line profiles.

We fit these profiles with the sum of two optically thin Gaussian components. The peak brightnesses and velocity dispersions are listed in Table 4. Errors are quoted which correspond to a doubling of χ^2 from its minimum value. About 80% of the line brightness (4–5 K) was associated with a broad component with a dispersion varying between about 9 and 18 km s^{−1}. The remaining 20% of the line brightness was attributed to a narrower component with a dispersion between about 3 and 4 km s^{−1}. Since beam-smearing accounts for such a large fraction of the observed linewidth (as indicated by the horizontal bar in each spectrum) it is very difficult to attach any physical interpretation to these line parameters.

3.7. Velocity Field Discontinuity Beyond the HBN

While a detailed analysis of the atomic gas kinematics is deferred to a subsequent paper, at least one specific aspect deserves comment at this time. Comparison of panels (a) and (c) of Figs. 1–10 in B95 reveals that the edge of the HBN distribution in each galaxy seems to be accompanied by a systematic discontinuity in the projected velocity field in the form of a kink in

the iso-velocity contours. The typical magnitude of the discontinuity is between 5 and 15 km s⁻¹, while its sense appears to be towards higher apparent rotation velocity in most cases. Only in the case of NGC 2366 does there appear to be a strong discontinuity in the sense of reduced apparent rotation velocity. Although most of these discontinuities are sufficiently subtle that they would not generally be classified as warps (eg. Briggs 1990) they are striking in their ubiquity. Inspection of high quality velocity fields and integrated H I emission images in the literature (eg. Begeman 1987) suggests that a subtle kinematic discontinuity is a very general phenomenon associated with the faint outer plateau of atomic gas beyond the star-forming disk. Although this kinematic signature is similar to the kink in iso-velocity contours associated with spiral arms at smaller radii, it is circular (and not spiral) in shape and occurs at the outer edge of the star-forming disk.

A more complex, but possibly related pattern is seen in the case of NGC 3031. Here the kinematics of the diffuse and the high brightness gas to the East of the inner disk are radically different. In this case an explanation must be sought in kinematic modelling of the entire tidally distorted gaseous envelope and condensed disks of the M81/M82 system. Less extreme forms of non-planar geometries and possibly non-axisymmetric dynamics should suffice to explain the more subtle kinematic distortions seen in the diffuse gas of other systems.

3.8. Absorption Properties

As discussed in B95, the small number of randomly distributed background sources brighter than about 5 mJy/beam have only a very low probability of occurring along a direction which intercepts the HBN of H I emission. A handful of tentative detections are presented there while the detected mean spin temperatures and the more stringent lower limits are also indicated at the relevant radii in the profiles of panel (a) of Figs. 3–9. What little data there are supports the general conclusion that only regions of high brightness have a relatively high opacity. Furthermore, the gas kinetic temperature within the inner disk is consistent with the brightness temperature seen directly in emission, implying H I opacities of unity or greater.

4. Discussion

Neutral hydrogen emission from the disks of spiral galaxies appears to be morphologically segregated into two distinct components. These are (a) a high brightness filamentary network (HBN) which is marginally resolved in the narrow dimension at about 150 pc and has velocity FWHM less than about 6 km s⁻¹ and (b) a diffuse inter-arm and outer disk component. Each component accounts for about one half of the total line flux, but it is the HBN which is coextensive with the star-forming disk; where it accounts for 60 to 90% of the H I line flux within R₂₅, from a region with face-on surface covering factor of about 15%. The narrow linewidth of the HBN profiles allows a strict upper limit of 300 K to be placed on the gas kinetic temperature. This cool

temperature allows the unambiguous identification of the HBN with the Cool Neutral Medium (CNM) predicted in theoretical treatments of H I thermodynamics in a galactic environment.

Positive radial gradients of the HBN peak brightness temperature are detected in all of the high and intermediate mass spiral galaxies in our sample. Only the low mass galaxy, NGC 2366, has a relatively flat distribution of HBN peak brightness with radius. It is interesting to compare the distributions of peak brightness observed in the various galaxies of our sample. They have been plotted together in Fig. 11, both in terms of the physical radius and in units of the blue stellar disk scalelength. Different symbols have been used to designate the different morphological types following the RC3 classifications. It is striking how the different distributions form an almost perfectly nested set with the earlier morphological types offset to lower temperatures at any given radius. The nesting appears to be somewhat better defined in the plot with physical units for radius rather than stellar scalelengths. The progression in morphological type is in this case also a progression in stellar surface density and almost certainly of the mass surface density.

Median emission spectra of the HBN display a narrow line core, but also high velocity wings, extending to at least plus and minus 50 km s^{-1} , which are well fit with a Lorentzian distribution. High velocity outflows seem to be intimately associated with the regions of highest gas opacity (as traced by high emission brightness), presumably due to embedded massive star formation. The detailed line-shape is found to vary in a systematic way with radius in each galaxy. Least squares fits to the line profiles in a simple radiative transfer model suggest a positive radial gradient of the H I kinetic temperature in all cases (excepting NGC 2366). The H I line core is fit well with a partially opaque isothermal gas distribution. Good agreement is found between the derived kinetic temperature and the measured peak brightness temperature in all cases but that of NGC 2366, together with a systematic departure in the outer disk of NGC 247, 4236 and possibly 7793. In the case of low mass spiral galaxies, the line-profile fitting suggests that the HBN becomes increasingly optically thin to $\lambda 21 \text{ cm}$ emission at large radii.

Our modeling of the emission line profiles indicates that the nested distributions of brightness temperature shown in Fig. 11 correspond to nested distributions of the H I kinetic temperature. The physical conditions responsible for determining the kinetic temperature (the gas phase metallicity, dust content, radiation field and interstellar pressure) yield a similar result in the outer disks of massive galaxies and in the inner disks of low mass systems. Further modelling should allow at least a crude determination of the radial variation of these physical properties. Simple considerations (e.g. Walterbos & Braun 1996) suggest that the expected radial variations in the gas phase metallicity, dust content and radiation field have only a marginal influence on the equilibrium kinetic temperature of the H I. The strongest variations in temperature seem to follow from a radial decline in the mid-plane hydrostatic pressure.

The HBN spectra can be contrasted with the H I emission spectra obtained for the solar neighbourhood by Kulkarni and Fich (1985). In that case, average spectra were formed for both the northern and southern galactic pole regions (NGP and SGP) using latitudes greater than

70° from the Bell Laboratories survey data. Although the NGP data are confused by a strongly infalling component, the SGP data are quite symmetric about the peak intensity. The peak brightness of the SGP spectrum is about 4 K and the profile has a FWHM of about 22 km s^{-1} . This linewidth would correspond to a gas kinetic temperature of about 8500 K if turbulent line broadening were negligible. Kulkarni and Fich interpret these spectra as arising in two or three physical components, of various temperatures and dispersions. An alternate interpretation might be that we are simply detecting almost pure Warm Neutral Medium (WNM) when we observe out of plane H I emission in the solar neighbourhood.

Taken together, these two results are consistent with the interpretation that spiral arms are dominated by high brightness, high opacity H I emission from the CNM (with kinetic temperatures in the range from 80 to 200 K), while inter-arm and presumably outer-disk regions are characterized by the low brightness emission of the WNM (with a kinetic temperature of about 8000 K). While this would not be a very surprising circumstance, it is gratifying that the first measurements that actually probe the global distribution of physical conditions in the atomic gas of external galaxies do support this view.

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Table 1. Log of Observations

Galaxy	R.A.(1950), Dec.(1950)	B or BnA	C or CnB	D or DnC	V_{Cen} (km/s)	N_{Ch}	Inc. (°)	PA (°)	R_{25} (")	Type	Dist. (Mpc)	B_T (mag)	L_B ($10^9 L_\odot$)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)
N55	00 12 24.00 −39 28 00.0	N/A	20-05-89	20-10-89	+140	64	80	110	972	Sc	2.0	8.22	3.2
N247	00 44 40.00 −21 02 24.0	04/05-03-89	20-05-89	20-10-89	+160	64	75	170	600	Sc	2.5	9.51	1.5
N2366	07 23 37.00 +69 15 05.0	19/28-03-89	29-11-90	01-12-89	+100	64	58	39	228	SBm	3.3	11.46	0.44
N2403	07 32 01.20 +65 42 57.0	19-03-89	29-11-90	01-12-89	+130	64	62	125	534	Sc	3.3	8.89	4.7
N3031	09 51 27.60 +69 18 13.0	16-03-89	29-11-90	01-12-89	−45	128	60	330	774	Sb	3.3	7.86	12.
N4236	12 14 21.80 +69 44 36.0	28-03-89	29-11-90	01-12-89	0	64	73	161	558	SBd	3.3	10.06	1.6
N4244	12 14 59.90 +38 05 06.0	23-03/02-05-89	29-11-90	30-11-89	+245	64	80:	233	486	Scd	4	10.60	1.4
N4736	12 48 32.40 +41 23 28.0	30-03-89	29-11-90	30-11-89	+305	64	33	305	330	Sab	3.8	8.92	6.1
N4826	12 54 16.90 +21 57 18.0	22-03-89	29-11-90	30-11-89	+415	128	66	300	282	Sab	3.8	9.37	4.0
N5457	14 01 26.60 +54 35 25.0	21-03-89	29-11-90	01-12-89	+230	64	27	40	810	Sc	6.5	8.18	35.
N7793	23 55 16.00 −32 52 06.0	04/05-03-89	20-05-89	20-10-89	+230	64	48	289	276	Sd	3.4	9.65	2.5

Table 2. Data Attributes and Results

Galaxy	a b p	Ω_B	ΔS_F	ΔT_F	ΔT_9	ΔT_{15}	ΔT_{25}	ΔT_{65}	$\int F_4 dV$	$\int F_0 dV$	I_{HBN}/I_T	Σ_{HBN}/Σ_T	Noise
(1)	(") (") (°)	(a.s. ²)	(mJy/bm)	(K)	(K)	(K)	(K)	(K)	(Jy-km s ^{−1})				(%)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)
N55	16.0 12.2 −15	220	3.5	10.9	...	...	3.98	0.93	1525	1525	0.72	0.29	...
N247	6.58 6.01 −10	61.6	1.9	21.1	12.7	6.47	3.78	0.76	765	860	0.82	0.50	2.4
N2366	5.67 5.66 −40	33.8	1.3	26.4	11.2	4.58	1.94	0.73	235	250	0.69	0.34	2.2
N2403	6.25 6.12 +66	48.0	1.2	17.2	9.73	4.85	2.52	0.68	1320	1440	0.58	0.26	2.0
N3031	6.13 5.84 −1	45.6	1.1	16.6	8.98	4.31	2.52	0.70	1455	1865	0.20	0.074	4.3
N4236	5.93 5.79 −38	49.2	1.2	16.8	8.98	4.85	2.52	0.63	550	610	0.74	0.43	1.0
N4244	6.84 5.95 −82	55.6	1.4	17.4	10.5	5.12	2.62	0.57	410	435	0.85	0.41	...
N4736	6.55 5.87 +85	48.8	1.3	18.3	9.73	4.58	2.23	0.58	43	70	0.26	0.057	...
N4826	6.49 6.10 −67	46.4	1.3	19.2	9.73	4.58	2.23	0.58	...	47	...	...	...
N5457	6.04 5.86 +69	44.8	1.1	16.8	8.23	4.31	2.43	0.62	1495	1880	0.34	0.13	2.6
N7793	6.98 6.06 −5	53.2	2.0	26.0	17.2	8.09	3.69	0.82	210	270	0.41	0.14	7.8

Table 3. Fits to HBN Spectra

Galaxy	Radius	T_C	Δ_L	N_{HC}	N_{HL}	τ_{max}	N_{HA}
	(")	(K)	(km/s)	(10^{21}cm^{-2})			(10^{21}cm^{-2})
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
N247	75	120^{+16}_{-15}	23^{+7}_{-7}	$2.5^{+4.0}_{-1.3}$	$4.0^{+0.5}_{-0.8}$	$4.5^{+7.1}_{-2.1}$	3.55
	225	109^{+6}_{-6}	20^{+3}_{-3}	$6.3^{+6.6}_{-3.7}$	$5.0^{+0.4}_{-0.5}$	$13^{+14}_{-7.5}$	4.03
	375	115^{+7}_{-7}	15^{+3}_{-2}	$4.0^{+5.4}_{-2.2}$	$5.0^{+0.4}_{-0.4}$	$7.7^{+10}_{-4.3}$	3.93
	525	156^{+10}_{-10}	20^{+3}_{-2}	$1.6^{+0.3}_{-0.3}$	$4.0^{+0.3}_{-0.2}$	$1.9^{+0.4}_{-0.3}$	3.71
	675	174^{+12}_{-12}	26^{+5}_{-4}	$2.0^{+0.6}_{-0.3}$	$4.0^{+0.5}_{-0.3}$	$2.1^{+0.7}_{-0.3}$	3.92
N2366	50	180^{+27}_{-27}	17^{+4}_{-2}	$1.0^{+0.5}_{-0.2}$	$6.3^{+0.7}_{-0.3}$	$1.0^{+0.5}_{-0.4}$	5.12
	150	232^{+40}_{-40}	20^{+2}_{-2}	$1.0^{+0.2}_{-0.2}$	$5.0^{+0.3}_{-0.4}$	$0.7^{+0.2}_{-0.2}$	4.56
	250	156^{+25}_{-20}	20^{+7}_{-6}	$2.5^{+2.5}_{-0.9}$	$4.0^{+0.6}_{-0.8}$	$3.1^{+3.0}_{-1.1}$	3.84
N2403	115	87^{+6}_{-4}	15^{+3}_{-2}	5.8^{+10}_{-4}	$3.9^{+0.3}_{-0.3}$	17^{+39}_{-12}	3.04
	340	90^{+5}_{-5}	13^{+3}_{-1}	4.8^{+8}_{-3}	$3.9^{+0.3}_{-0.3}$	13^{+25}_{-9}	2.99
	565	94^{+4}_{-4}	20^{+5}_{-3}	18^{+9}_{-7}	$2.7^{+0.2}_{-0.3}$	50^{+23}_{-18}	2.62
	790	94^{+5}_{-5}	35^{+13}_{-13}	28^{+26}_{-10}	$2.2^{+0.4}_{-0.4}$	72^{+69}_{-26}	2.41
	1015	108^{+11}_{-12}	35^{+43}_{-16}	11^{+11}_{-7}	$1.8^{+0.7}_{-0.7}$	22^{+23}_{-15}	2.22
N3031	275	87^{+9}_{-9}	13^{+5}_{-4}	4.0^{+10}_{-3}	$3.2^{+0.2}_{-0.6}$	12^{+42}_{-8}	2.58
	385	90^{+6}_{-5}	13^{+4}_{-3}	10^{+20}_{-7}	$2.5^{+0.6}_{-0.2}$	28^{+60}_{-18}	2.31
	495	96^{+5}_{-5}	15^{+3}_{-2}	$2.5^{+2.4}_{-1.0}$	$3.2^{+0.2}_{-0.2}$	$6.3^{+6.0}_{-2.5}$	2.72
	605	101^{+6}_{-6}	20^{+4}_{-4}	$5.0^{+5.0}_{-2.8}$	$3.2^{+0.3}_{-0.3}$	12^{+12}_{-7}	2.90
	715	104^{+7}_{-7}	17^{+6}_{-5}	$5.0^{+6.5}_{-2.8}$	$2.5^{+0.3}_{-0.3}$	11^{+15}_{-6}	2.52
N4236	75	86^{+9}_{-9}	13^{+5}_{-3}	$3.2^{+32}_{-2.6}$	$4.0^{+0.6}_{-0.6}$	9^{+95}_{-8}	2.95
	225	88^{+5}_{-5}	13^{+2}_{-2}	$3.2^{+10}_{-1.9}$	$4.0^{+0.3}_{-0.3}$	9^{+27}_{-5}	2.98
	375	102^{+8}_{-8}	15^{+2}_{-2}	$1.0^{+0.9}_{-0.4}$	$4.0^{+0.3}_{-0.3}$	$2.3^{+2.1}_{-0.8}$	3.12
	525	123^{+15}_{-9}	13^{+2}_{-2}	$0.8^{+0.4}_{-0.2}$	$3.2^{+0.3}_{-0.2}$	$1.4^{+0.6}_{-0.3}$	2.73
	675	162^{+73}_{-26}	13^{+3}_{-3}	$0.6^{+0.3}_{-0.2}$	$2.5^{+0.5}_{-0.2}$	$0.7^{+0.4}_{-0.2}$	2.42
N5457	100	98^{+15}_{-10}	17^{+7}_{-5}	$2.0^{+4.0}_{-0.9}$	$2.5^{+0.4}_{-0.5}$	$4.9^{+12}_{-2.3}$	2.38
	300	84^{+8}_{-6}	17^{+8}_{-7}	32^{+180}_{-26}	$3.2^{+0.6}_{-0.6}$	98^{+570}_{-78}	2.75
	500	110^{+10}_{-10}	15^{+4}_{-2}	$2.0^{+2.3}_{-0.9}$	$4.0^{+0.3}_{-0.5}$	$4.2^{+4.7}_{-2.0}$	3.28
	700	127^{+6}_{-6}	17^{+3}_{-3}	$4.0^{+2.1}_{-1.2}$	$3.2^{+0.3}_{-0.2}$	$6.7^{+3.5}_{-2.0}$	3.13
	900	145^{+10}_{-10}	20^{+7}_{-6}	$6.3^{+6.0}_{-2.7}$	$4.0^{+0.5}_{-0.2}$	$8.7^{+8.0}_{-3.7}$	3.93
N7793	50	129^{+25}_{-25}	42^{+65}_{-27}	$10^{+58}_{-7.5}$	$3.5^{+1.7}_{-1.6}$	16^{+94}_{-12}	3.52
	150	129^{+10}_{-10}	17^{+9}_{-5}	$7.4^{+8.5}_{-4.4}$	$3.5^{+0.7}_{-0.6}$	12^{+14}_{-7}	3.44
	250	150^{+30}_{-30}	25^{+21}_{-12}	$3.5^{+5.4}_{-2.0}$	$3.0^{+1.4}_{-0.9}$	$4.6^{+7.1}_{-2.6}$	3.30

Table 4. Fits to Diffuse Disk Spectra

Galaxy	Radius	T_{B1}	σ_1	T_{B2}	σ_2
	(")	(K)	(km/s)	(K)	(km/s)
(1)	(2)	(3)	(4)	(5)	(6)
N5457	200	$4.7^{+0.2}_{-0.2}$	$18.^{+1}_{-1}$	$1.4^{+0.6}_{-0.5}$	$4.3^{+2.6}_{-1.7}$
	600	$3.5^{+0.4}_{-0.3}$	$13.^{+2}_{-2}$	$1.7^{+0.7}_{-0.6}$	4.5^{+2}_{-2}
	1000	$3.3^{+0.2}_{-0.2}$	$11.^{+0.6}_{-0.6}$	$1.2^{+0.7}_{-0.2}$	$2.8^{+0.9}_{-0.9}$
	1400	$3.7^{+0.3}_{-0.3}$	$8.7^{+1.0}_{-1.0}$	$0.9^{+0.9}_{-0.5}$	3^{+4}_{-2}

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Fig. 1.— Illustration of noise properties in the database. **(a)** A histogram of the observed brightness in several spectral channels containing no discernible line emission. The solid curve is a Gaussian with $\sigma = 1.05$ mJy/Beam area. The dashed curve corresponds to $\sigma = 1.07$ mJy/Beam area. **(b)** A histogram of the velocities isolated by the mask in a subsection of Fig. 2c. **(c)** The histogram of velocities in the same region which also satisfy: associated pixel brightness $> 3 \sigma$. **(d)** The histogram of velocities in the same region which also satisfy: associated pixel brightness $> 4 \sigma$.

Fig. 2.— Illustration of data purity in the database. **(a)** The peak brightness of H I emission in NGC 5457 is shown (as in B95). **(b)** The same image after application of a spatial mask (as described in the text). **(c)** The line-of-sight velocities of those pixels shown in (b). **(d)** The line-of-sight velocities which also satisfy: associated pixel brightness $> 3 \sigma$.

Fig. 3.— Radial profiles and spectra of the high brightness network of H I in NGC 247. **(a)** Filled circles indicate the peak brightness (the 80th percentile) at full spatial resolution, open circles the kinetic temperature fit to the line profiles, open squares the apparent face-on mass surface density, and the solid line is the face-on blue light surface brightness. Open triangles with error bars are the isolated measurements of mean spin temperature made against continuum sources. Half error bars indicate 3σ lower limits to the mean spin temperature. **(b)** Spatial and velocity coherence. Filled circles indicate the peak brightness as in (a), the other symbols represent the median ratio of diminished peak brightness (see text) after smoothing to 9 arcsec: open circles, 15 arcsec: open squares, 10 km s^{-1} : three arm star and 20 km s^{-1} : six arm star. **(c)** Filled circles indicate the peak brightness as in (a), open circles the face-on surface covering factor of the HBN, stars indicate the local fraction of H I flux contained in the HBN. The short-dashed line is the accumulated flux in the HBN normalized to the total flux. The long-dashed line is the normalized accumulated total flux. **(d)** Median, co-aligned emission line profiles of brightness temperature within annular elliptical zones at the indicated radii. The solid line is the fit tabulated in Table 3.

Fig. 4.— Radial profiles and spectra of NGC 2366 with panels as in Fig. 3.

Fig. 5.— Radial profiles and spectra of NGC 2403 with panels as in Fig. 3.

Fig. 6.— Radial profiles and spectra of NGC 3031 with panels as in Fig. 3.

Fig. 7.— Radial profiles and spectra of NGC 4236 with panels as in Fig. 3.

Fig. 8.— Radial profiles and spectra of NGC 5457 with panels as in Fig. 3.

Fig. 9.— Radial profiles and spectra of NGC 7793 with panels as in Fig. 3.

Fig. 10.— Median co-aligned emission line profiles of diffuse disk emission in NGC 5457 within annular elliptical zones at the indicated radii and with peak $T_B < 7.5 \text{ K}$. The expected degree of beam-smearing due solely to galactic kinematics (at this resolution of $65''$) is indicated by the horizontal bar. The solid lines are the fits tabulated in Table 4.

Fig. 11.— Radial profiles of peak brightness temperature in the sample galaxies. **(a)** Peak brightness (the 80th percentile) is plotted as a function of physical radius with different symbols for the different morphological types. Solid lines connect the points for individual galaxies. **(b)** Peak brightness is plotted as a function of radius in units of the blue stellar disk scalelength.



















